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**Experimental Study of the Exchange Flow through a Horizontal Ceiling Vent in Atrium Fires**

**Criteria of Supply Air and Pressure necessary for Uni-directional Flow**

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## ABSTRACT

This study is directed at understanding the exchange flow through a single top vent in an atrium-type of compartment via fire trials, and obtaining fundamental knowledge of physical mechanism necessary to develop a comprehensive atrium fire model. This study focuses on the supply air and pressure boundary conditions required to prevent flow entering thorough the top vent from outside of the compartment, when the supply air into the compartment is limited. A series of experiments were conducted in a scaled cubical compartment with a natural gas burner as a heat source. Under various heat release rates with different forced air supply, the criteria distinguishing the flow between bi-directional flow and uni-directional out going flow were examined. The result indicates that the criteria can be characterized by dimensionless parameters of the Froude Number and/or the pressure difference, which are functions of the temperature difference between inside and outside of the compartment .

Also, The data obtained in this experiment agrees with the existing equation proposed in the past, however, some discrepancies are found in the pressure difference boundary. The modification and definition of the pressure difference are remained as the future task.

## 1. INTRODUCTION

Many buildings with atria spaces have been build for the last decade in Japan as well as in other countries, and adjacent rooms to atrium tends to become more open to the atrium to design spectacular space. From the view point of fire safety, rapid smoke spread through atrium is one of the major concerns in case of fire. Even if there are smoke barriers between surrounding spaces and atrium, smoke layer will be falling down gradually and the whole atrium space will be contaminated with fire smoke at last, unless sufficient ventilation is installed.

Usually, natural ventilation is used to prevent the smoke layer falling as shown in Fig. 1(a). This chimney type smoke ventilation can work effectively, while sufficient top vent and supply air from lower part are given. However when there are not enough supply air, fresh air may thrust the upper hot layer and it make smoke spread rapidly in the lower area as shown in Fig. 1(b). This causes problems for fire fighters' activity as well as occupants' evacuation. Recent buildings with atrium are getting larger and tend to be difficult to get sufficient supply air. For the above reason, criterion of the necessary supply air or pressure difference at the top vent to prevent incoming flow is one of the important information for fire safety design of atrium space.

A series of scaled model experiments have been carried out to study the flow through a horizontal single top vent with a fire inside the atrium. A part of the results has been reported on the exchange flow rate through the top vent under no air supply condition[1]. This study focuses on the horizontal top vent flow behavior with forced air supply vent from the bottom of the model compartment, especially criteria distinguishing the flow between bi-directional and uni-directional flow. A few theoretical studies have been reported on this problem. Dr. L. Cooper[2] addressed this phenomena recently and proposed a model of "combined buoyancy- and pressure- driven flow through a horizontal vent". There are small number of experimental data available, and his model was based on the limited number of experiments in the past [3][4]. Some comparisons between experimental data and proposed model were made and examined the correlation between the temperature difference and dimensionless parameters, i.e. the Froude Number and Pressure difference.

## 2. DESCRIPTIONS OF THE EXPERIMENTS

### 2.1. Reduced-Scale Experiments

Reduced scale tests were conducted to study the conditions distinguishing between uni-directional and bi-directional flow through a circular, horizontal, top-centered vent (diameter, 0.15m). A cubic test compartment (0.8 m inside) was constructed of 0.05 m (0.025m at ceiling, 0.0125m at ceiling near the vent) thick ceramic fiber board and it was covered by aluminum metal plate to get higher air tightness. This compartment was installed above an air supply chamber as shown in Fig. 2. One 0.15 m diameter natural gas (11,000 Kcal/Nm$^3$) burner was located flush with the floor and at the center of the compartment. To avoid the direct influence from air supply flow to the fire source, the burner is located on the center of the 0.3m square ceramic plate. The gas flow rate was controlled to get heat release rate ranging from 1.1 to 3.5 kW. Under each fixed heat release rate condition, fresh air was supplied at the floor surface. This floor was made of glass fiber covered with meshed metal plate to give an uniform velocity profile ventilation. This forced ventilation rate was set to make uni-directional flow through top vent at first, then reduced step by step to change the flow to the bi-directional flow. The range of ventilation rate was between .300 and .180 m$^3$/min. in ambient temperature. The measurements as follows were carried out under quasi-steady state. For careful measurements, it took more than two hours to start measurements after changing the supply air flow rate.

### 2.2. Measurements' Installation

Temperature distribution :

Inside the test compartment were five horizontal thermocouple of trees ( type K with 0.127 mm beads) with 15 measuring points at different levels height, and one vertical thermocouple with 17 measuring points to measure gas temperature profile. The data was recorded every 12 seconds during 10 minutes after one monitor temperature installed at the center of the top vent became stable. Also ambient temperature was measured at 5 cm above the compartment as shown in Fig.2.

Pressure difference between inside and outside of the compartment :

The pressure difference between inside and outside was measured with pressure transducer, which resolution was within 0.01 Pa. The pressure taps made of 1.6 mm i.o. metal tube were installed at the same level of immediately below the ceiling. The out put of the transducer was recorded every 25 msec. during 2 minutes by 6 times for each test run. The pressure difference reported hereafter is the time averaged data during 12 minutes' data.

Observation of uni-directional/bi-directional flow through top vent :

To distinguish the vent flow between uni-directional and bi-directional flow, temperature fluctuation was measured with very thin thermocouple of 13μmϕ at the ceiling level, 1 cm apart from the top vent edge. The temperature was measured every 25 msec in the same manner as the pressure difference measurements. And the bi-directional flow mode is decided by the temperature to reach ambient temperature. Also, visualization with smoke of incense at the top vent edge was refereed for final decision.

The conditions of each test run and some of the principle data are shown in Table 1, and it is found that the Grashof Number is in the range between $2.1 \times 10^7$ and $4.5 \times 10^7$ in this experiment.

## 3. DISCUSSION

### 3.1. Temperature Profile and Normalized Temperature Difference

Table 1 shows both conditions of uni- and bi-directional flows under each of the heat release rate condition. Also time and space averaged temperature in side the compartment at level **A** ( 3 cm below the ceiling) are listed. The Fig. 3 shows examples of the average temperature profile inside the compartment when the heat release rate is 1.08 kW. Fig. 3(a) is the case of uni-directional flow under relatively high air supply condition. Whereas, (b) is a typical temperature profile under no air supply condition which makes bi-directional flow at the top vent. Fig. 3(b) indicates that the fresh air enters the compartments along the edge of the top vent, and it was observed that fresh air thrust through the hot smoke layer and was well mixed quickly. As the result, temperature profile became relatively flat except fire plume region. The profile became more flat in the case of uni-directional, and the temperature varies a little and relatively stable. For the following discussion, a dimensionless temperature rise is defined by the following equation.

$$\varepsilon = (T_f - T_{amb}) / ((T_f + T_{amb}) / 2) \qquad \text{Eq.(1)}$$

where T is the absolute Temperature, the subscript $_{amb}$ and $_f$ refer to ambient temperature and averaged temperature at the level **A** in the compartment respectively.

### 3.2. Dimensionless Flow Rate and Pressure Difference

The phenomena of the combined buoyancy- and pressure- driven flow through a horizontal vent was studied by L. Cooper[2]. The following two dimensionless parameters of flow rate (Fr) and pressure difference (Π) are adopted as to distinguish the flow between uni- and bi- directional flow. This dimensionless flow rate is known as the Froude Number.

$$Fr,_{FLOOD} = (V_{FLOOD} / A) / (2gD\varepsilon)^{1/2} \qquad \text{Eq. (2)}$$

$$\Pi_{FLOOD} = \Delta P_{FLOOD} / (4g\varepsilon\rho D) \qquad \text{Eq. (3)}$$

Where V [$m^3/s$] is the volumetric flow rate through top vent. This value is estimated by using the supply air flow rate of ambient temperature and the averaged temperature at the level **A**. A is the area of top vent (0.071[$m^2$]), g the gravity acceleration, D the vent diameter (0.15[m]) and ρ is the average density of the flow[$kg/m^3$]. Subscript $_{FLOOD}$ is the boundary between uni- and bi-directional flow mode.

Δ P[Pa] is the pressure difference between bottom and upper side of the horizontal top vent. In this experiment, the pressure difference was measured at the same level height immediately below the ceiling and reference pressure is selected in upper side of the top vent. Then the value is supposed to be positive to make uni-directional flow from bottom to upper side. However the pressure difference was so small that data obtained indicated that statistic pressure inside the compartment was negative against the outside at the same level height, even the fresh air was supplied from the bottom of the compartment. This seems to be caused by a buoyant plume above the top vent, which works as if it pumps up the fluids from the compartment. To simplify the mechanism of the flow behavior through the top vent, the flow is assumed to be driven by the pressure difference between bottom and upper sides. Some modification for the pressure difference data obtained is needed by adding the hydrostatic pressure as expressed below.

$$\Delta P = \Delta P_{Exp} + \rho_{amb}\, g\, H \qquad \text{Eq. (4)}$$

Where H [m] is vertical distance between bottom and upper reference pressure points. Subscript $_{Exp}$ is of the readings in this experiment. H seems to depend on the depth of the top vent, however the definition of the reference pressure points are ambiguous. To proceed the further discussion, the value H is set to be 3.5 times of depth of the top vent empirically, which gives similar magnitude pressure difference by using the theoretical correlation proposed in the past[2]

### 3.3. Criteria Characterizing Flow Mode

Fig.4 shows the correlation between both the Froude Number (Fr) and the dimensionless pressure difference ($\Pi$) versus dimensionless temperature difference ($\varepsilon$). Solid symbols stand for the uni-directional flow and open symbols bi-directional flow. The figure indicates that the criteria distinguishing two flow mode is in the narrow range. The criterion of the Froude number increases gradually with increasing temperature difference. The experimental equation is obtained by using the least square method as follows.

$$Fr,_{FLOOD} = 0.274\exp(0.6987\varepsilon) \qquad \text{Eq. (5)}$$

The value of the criterion is almost 60% higher than the equation proposed in the past[2], which is expressed as 0.175 exp (0.544 $\varepsilon$ ), however an expression of the correlation is similar. This difference seems to be caused by the definition of the bi-directional flow. In this experiments, when relatively small transient inflow is observed, it is classified as the bi-directional flow. This may gives higher Froude number. Whereas the curve of dimensionless pressure ($\Pi$) versus $\varepsilon$ is different from the correlation as follows which was proposed in the past [2].

$$\Pi_{FLOOD} = (1-\varepsilon/2)Fr^2{}_{FLOOD} / (4C^2{}_{D,FLOOD}) \qquad \text{Eq. (6)}$$

where $C_{D,Flood}$ is the flow coefficients of the top vent and 0.171 is proposed . When this orifice coefficient is constant, the dimensionless pressure increases as increasing the Froude number. However, experimental data obtained indicates that the dimensionless pressure difference decrease as increasing the temperature difference, even if another hydrostatic pressure is assumed. Fig.5 is the plots between the parameter (1-$\varepsilon$/2) $Fr^2$ versus the dimensionless pressure difference($\Pi$). This figure shows that the boundary is dependent mainly on the (1-$\varepsilon$/2) $Fr^2$ parameter and not the pressure difference. Also the flow coefficient seems to vary. For this reason, the Froude Number is more appropriate than the pressure difference as a design criterion to prevent inflow through the horizontal top vent. Further experiments under different vent sizes are expected to verify the criterion correlation expressed by the above dimensionless parameters.

## 4. Concluding Remarks

A series of experiments were conducted to ascertain the criteria correlation which characterizes the uni- and bi-directional flow pattern through top vent under forced ventilation condition. The

experimental result indicates the followings.
1. The criteria of the dimensionless flow velocity (Fr) can be expressed as an function of the dimensionless temperature ($\varepsilon$) such as $0.27\exp(0.70\varepsilon)$. This is similar to the equation obtained in the previous work. However, the value of this experiment is almost 60% higher .
2. The behavior of combined buoyancy and pressure driven flow through a horizontal top vent is somewhat complex, especially due to flow coefficient change. Then it is not practical to adopt the pressure difference as a design criterion.
3. The flow through the top vent seems to depend on more macroscopic flow, i.e. plume above the top vent. It causes a negative statistic pressure inside the compartment, even if a certain fresh air is supplied from the bottom. The effect of the plume should be taken into account for examining this physical phenomena in future.

**References**

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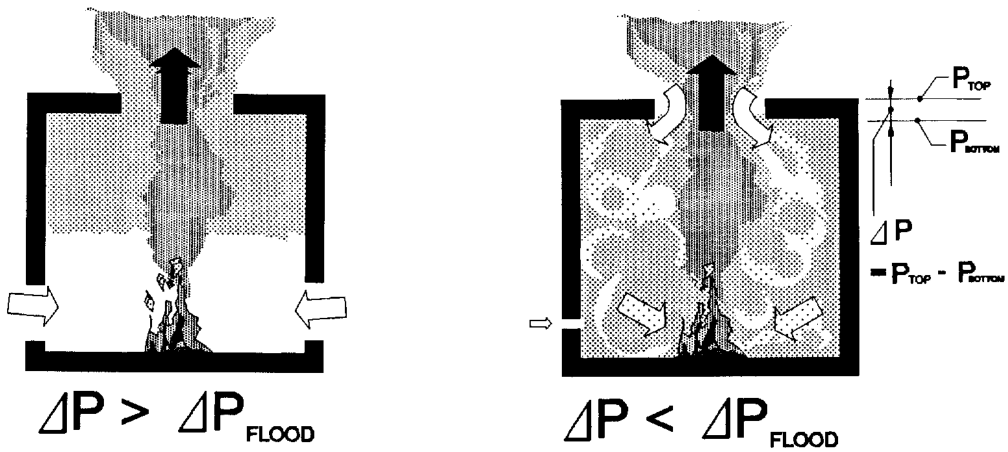
4) M.Epstein, M.Kenton, "Combined Natural Convection and Forced Flow through Small Openings in a Horizontal Partition with Special Reference to Flows in Multi- compartment Enclosure", J.of Heat Transfer, Vol.111, p.980-987,1989




**(a) Uni-directional Flow** **(b) Bi-directional Flow**

**Figure 1. Schematic flow mode at a horizontal top vent in case of atrium fire**

(c.f. $\Delta P_{Flood}$ is the pressure difference critical boundary between uni-directional (floodind) and bi-directional flow)

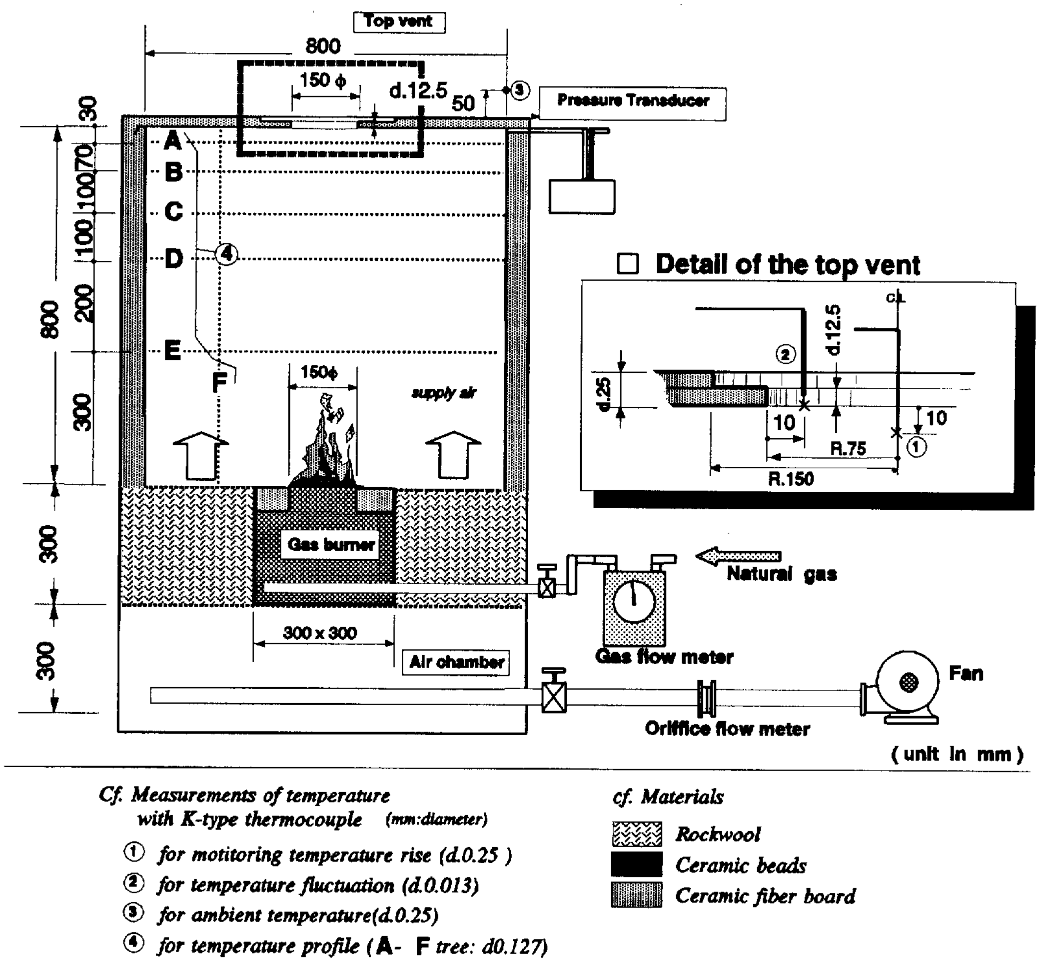
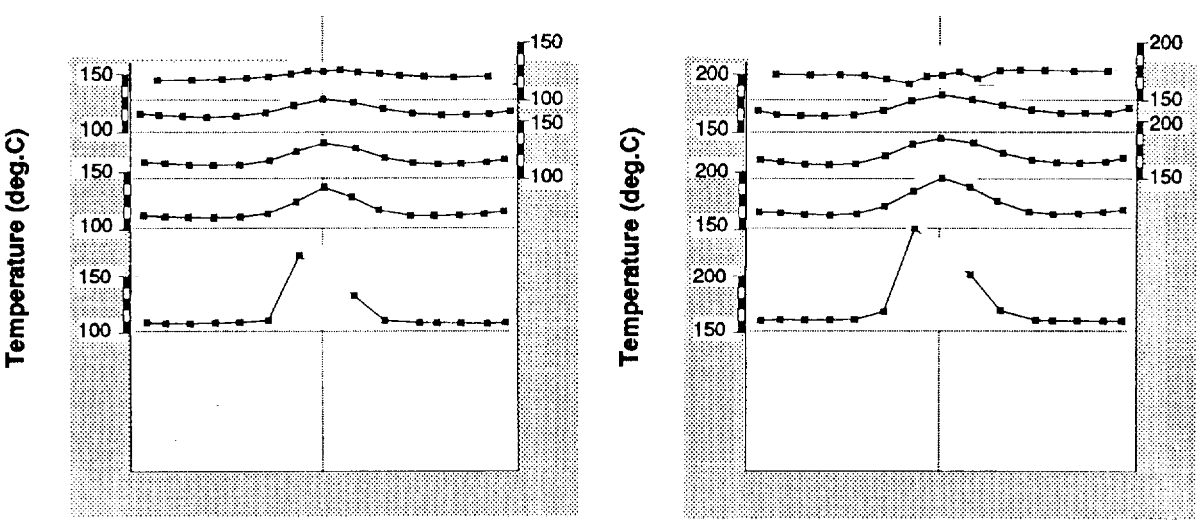



**Figure 2. Sketch of experiment**

## Table1. Data from the present experiments

| Heat Release Rate ($Q_f$) [Kw] | Air Supply Rate($V_f$) *1) [SLM] | Flow Direction Direction (uni- / bi-) | Temperature Ambient [℃] | Temperature Inside [℃] | Pressure Difference [Pa] |
|---|---|---|---|---|---|
| 1.08 | no supply | bi | 21.0 | 172.1 | -0.276 |
| 〃 | 187 | bi | 19.2 | 127.9 | -0.211 |
| 〃 | 240 | bi | 20.0 | 127.9 | -0.165 |
| 〃 | 251 | uni | 19.6 | 122.5 | -0.145 |
| 1.41 | 252 | bi | 13.9 | 144.3 | -0.173 |
| 〃 | 274 | uni | 11.0 | 140.5 | -0.158 |
| 1.94 | 290 | bi | 19.8 | 198.2 | -0.183 |
| 〃 | 314 | uni | 20.9 | 192.8 | -0.148 |
| 2.42 | 291 | bi | 22.8 | 225.0 | -0.132 |
| 〃 | 310 | uni | 22.0 | 217.9 | -0.153 |
| 3.11 | 307 | bi | 22.7 | 280.6 | -0.174 |
| 〃 | 320 | uni | 20.8 | 273.8 | -0.130 |
| 3.48 | 287 | bi | 24.6 | 303.5 | -0.225 |
| 〃 | 313 | uni | 24.6 | 292.6 | -0.200 |

*cf. 1) Volumetric flow rate at 15℃. 2) bi-/uni- directional flow.*
*3) Time and 15 measuring points averaged data at 3 cm below the ceiling.*
*4) Pressure difference between inside and outside at the same level hight of immediately below the ceiling. Negative pressure means that the pressure is negative against the outside.*




**(a) Uni-directional Flow**
*(No air supply)*

**(b) Bi-directional Flow**
*( Supply air = 251slm )*

**Figure 3. Example of temperature profile in test compartment : (Heat release rate : $Q_f$= 1.08 kW)**

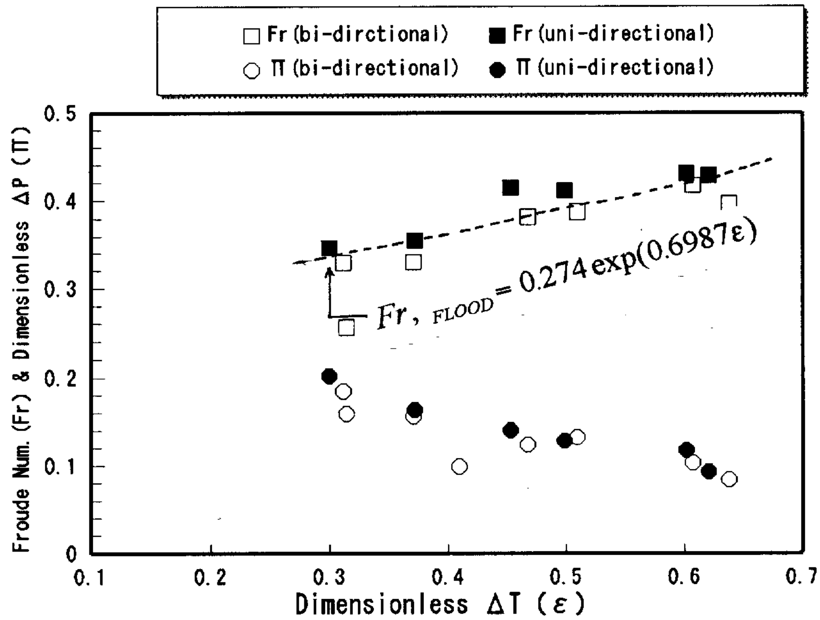



**Figure 4. Correlations between dimensionless parameters (Fr, Π) vs dimensionless temperature differnce( ε )**

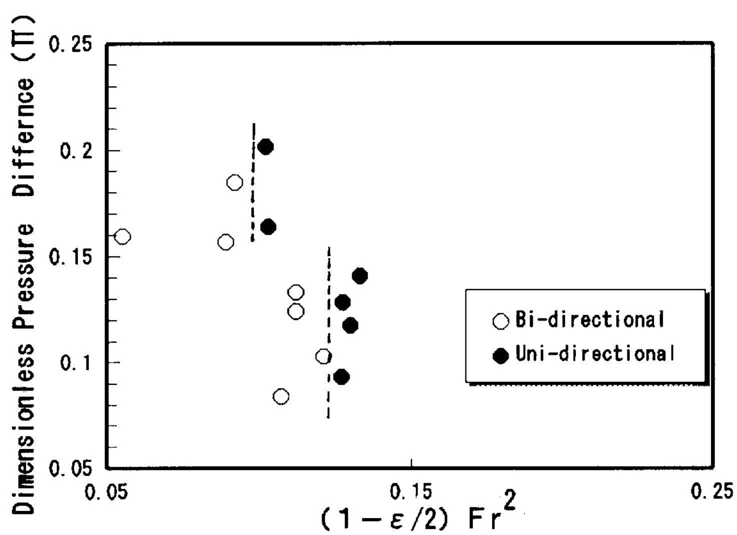



**Figure 5. Plots of dimensionless parameter ((1- ε /2)*Fr$^2$) vs dimensionless pressure difference (Π)**

### *Discussion*

Edward Zukoski: I just did a back-of-the-paper computation of the velocity and the plume inside. A free standing plume would have a velocity of about 1 m/s on the center line. Would that cause some problems?

Tokiyoshi Yamada: At this moment, I have no idea. But it may.

Howard Emmons: In my paper, I indicated many points that needed more data. I wish I'd had this about two months ago.

Tokiyoshi Yamada: Actually, this data existed two months ago and this made me aware of how important data exchange is.

Patrick Pagni: Let me close with one simple, practical question. If the air supply is equal to the volume flow out the ceiling vent, is it unidirectional flow?

Tokiyoshi Yamada: Not necessarily. In terms of volume, what goes in is not equal to what comes out because what goes in would be expanded and thus we have to take the expansion into consideration.